(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
14 August 2003 (14.08.2003)

PCT

(10) International Publication Number
WO 03/066916 A2

(51) International Patent Classification[7]: C22C

(21) International Application Number: PCT/US03/01682

(22) International Filing Date: 21 January 2003 (21.01.2003)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
10/066,830 4 February 2002 (04.02.2002) US

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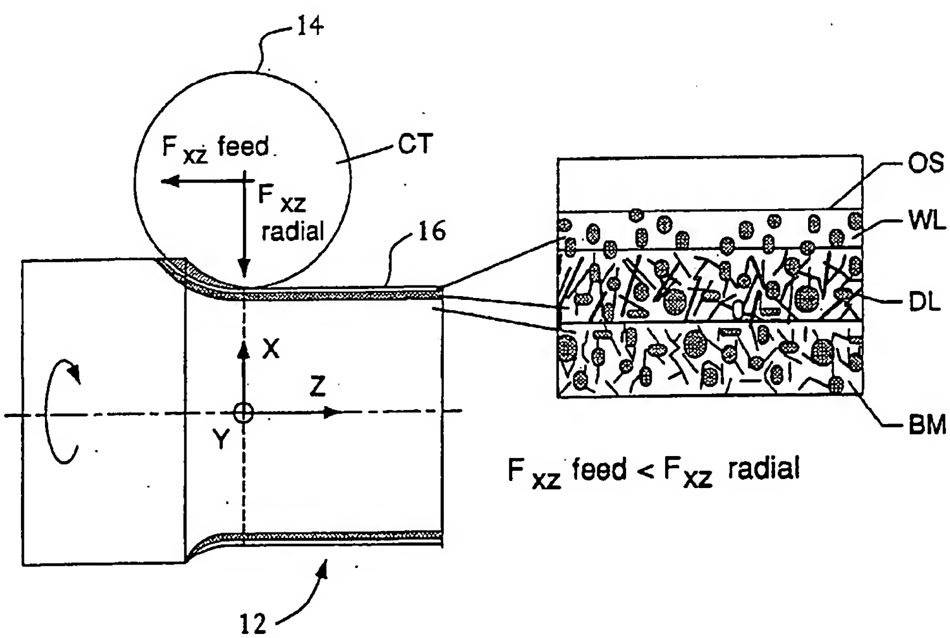
(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW),

[Continued on next page]

(54) Title: APPARATUS AND METHOD FOR MACHINING OF HARD METALS WITH REDUCED DETRIMENTAL WHITE LAYER EFFECT



(57) Abstract: An apparatus and a method are disclosed for reducing a thickness of a thermomechanically-affected layer on an as-machined surface of a hard metal workpiece being machined by a hard cutting tool exerting a thermomechanical load on a surface of the workpiece. The method involves reducing the thermomechanical load on the surface of the workpiece, and the apparatus includes a means for reducing the thermomechanical load on the surface of the workpiece.

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Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— *without international search report and to be republished upon receipt of that report*

APPARATUS AND METHOD FOR MACHINING OF HARD METALS WITH REDUCED DETRIMENTAL WHITE LAYER EFFECT

BACKGROUND OF THE INVENTION

The present invention relates to the field of machining of hard metallic materials by cutting (*e.g.,* shaping parts by removing excess material in the form of chips) with hard cutting tools, and more particularly to machining methods that reduce the thickness of a thermomechanically-affected layer (*e.g.,* white layer) on as-machined surfaces of hard metal workpieces and/or mitigate the detrimental effects in machined surfaces of hard metal workpieces due to the thermomechanical load of a hard cutting tool machining the workpiece.

Specifically, the invention concerns machining of hard metallic parts, characterized by the surface hardness exceeding 42 Rockwell on Scale C, with hard cutting tools, characterized by the edge hardness exceeding 1500 Vickers. Machining of hard or hardened metallic parts brings about significant cost savings to the manufacturing industries through the reduction of heat-treating and machining steps in the production cycle and minimizing the extent of slow, finish-grinding operations. With the advent of hard, ceramic cutting tools and tool coatings, which include alumina (Al_2O_3), cubic boron nitride (CBN) and many other advanced materials, machining of hard metals has become feasible and includes outer diameter (OD) turning, inner diameter turning (boring), grooving, parting, facing, milling, drilling, and numerous other cutting operations.

A significant limitation of the widespread use of hard metal machining is the so-called "white layer" effect, a microscopic alteration of the as-machined surface of a workpiece, which effect is produced in response to an extremely high thermomechanical load exerted at the as-machined surface by the cutting tool. Although not fully understood, the thermomechanically-affected workpiece surface comprising an etching-resistant white layer is undesired because of associated tensile stresses, *e.g.*, reduced fatigue-resistance, lower fracture toughness, and/or reduced wear resistance of parts produced. See, B.J. Griffins, *White Layer Formation at Machined Surfaces and Their Relationship to White Layer Formations at Worn Surfaces*, J. of Tribology, April 1985, Vol. 107/165.

It has been reported that a sharper and/or not worn cutting edge, as well as the conventional flooding of a cutting tool with a water-based, emulsified oil coolant, contribute to the reduction in the detrimental tensile stresses and white layer. W. Konig, M. Klinger, and R. Link, *Machining Hard Materials with Geometrically Defined Cutting Edges – Field of Applications and Limitations*, Annals of CIRP, 1990, Vol. 57, pp. 61-64. Hard machining

with conventional flood cooling has been reexamined but found to be ineffective. H.K. Tonshoff and H.G. Wobker, *Potential and Limitations of Hard Turning*, 1st Int. Machining and Grinding Conf., Sept. 12-14, 1995, Dearborn, MI, SME Technical Paper MR95-215. Moreover, sharp-finished cutting edges easily fracture in the case of inexpensive, Al_2O_3-based tools, leaving expensive CBN tools as the only current option. It has been noted that the use of coolants in hard machining should be avoided since cooling accelerates the edge wear and shortens overall life of CBN tools used for finish-hardturning. T.J. Broskea, *PCBN Tool Failure Mode Analysis*, Intertech 2000, Vancouver B.C., Canada, July 17-21, 2000. Numerous other publications and machining textbooks have indicated that the use of coolants with inexpensive Al_2O_3 tools brings about a rapid fracture. Using non-cooled CBN tools (dry turning), the effect of cutting speed on white layer thickness during hardturning of a popular hardened bearing steel 52100 has been examined. Y.K. Chou and C.J. Evans, *Process Effects on White Layer Formation in Hard Turning*, Trans. of NAMRI/SME, Vol. XXVI, 1998, pp.117-122. Results showed that only relatively low cutting speeds, translating into reduced productivity rates, assure an acceptably thin white layer. Thus, the machining technology of today offers no solution for making hard, white layer-free parts quickly and at reduced costs.

It is desired to have an apparatus and a method which minimize the alteration of workpiece surfaces during hard machining, and more specifically, which eliminate or minimize tensile and/or fluctuating surface stresses and etch-resistant white layer (*i.e.*, the detrimental effects of "white layer").

It is further desired to have an apparatus and method which produce better parts having less of the detrimental effects of a thermomechanically-affected layer (*e.g.*, "white layer") and which do so faster, at lower costs, and with less expensive tools.

BRIEF SUMMARY OF THE INVENTION

Applicants' invention is an apparatus and a method for reducing a thickness of a thermomechanically-affected layer on an as-machined surface of a hard metal workpiece, and an apparatus and a method for mitigating a detrimental effect of a thermomechanical load in a machined surface of a hard metal workpiece. Another aspect of the invention is an apparatus and a method for machining a hard metal workpiece using the aforesaid apparatuses and methods. Other aspects of the invention are the workpieces machined by the apparatus and method for machining.

A first embodiment of the method for reducing a thickness of a thermomechanically-affected layer on an as-machined surface of a hard metal workpiece being machined by a

hard cutting tool exerting a thermomechanical load on a surface of the workpiece includes reducing the thermomechanical load.

There are several variations of the first embodiment of that method. In one variation, the hard metal workpiece includes an iron-containing alloy. In another variation, the hard cutting tool is made at least in part of a material selected from a group containing a ceramic compound; a ceramic-ceramic composite; a ceramic-metal composite; a diamond-like, metal-free material; an alumina-based ceramic; a cubic boron nitride-based ceramic material; a tungsten carbide-based material; and a cermet-type material.

In another variation, the cutting tool initially has a first temperature prior to contacting the surface of the workpiece, and the thermomechanical load is reduced by cooling the cutting tool to a second temperature lower than the first temperature before the cutting tool contacts the surface of the workpiece or while the workpiece is being machined. In a variant of that variation, the cutting tool is cooled by an external cooling means. In one variant of that variant, the cooling means includes at least one cryogenic fluid. In another variant, the cooling means includes at least one inert, water-free coolant. In yet another variant, the cutting tool has a hardness and a resistance to cracking, and cooling the cutting tool with the cooling means results in an increase in the hardness or an increase in the resistance to cracking.

In another variation of the method, at least a portion of the thermomechanical load is a component of a cutting force, the component being applied in a direction normal to the surface of the workpiece, and the thermomechanical load is reduced by reducing the component of the cutting force. There are several variants of this variation. In one variant, the cutting tool has an inclination angle, and the component of the cutting force is reduced by making the inclination angle more positive. (The phrase "making the inclination angle more positive" is defined and discussed in the Detailed Description of the Invention section below.) In another variant, the cutting tool has a rake angle, and the component of the cutting force is reduced by making the rake angle more positive.

A second embodiment of the method for reducing a thickness of a thermomechanically-affected layer on an as-machined surface of a hard metal workpiece being machined by a hard cutting tool includes multiple steps. In this embodiment, the cutting tool initially has a first temperature prior to contacting the surface of the workpiece and exerts a thermomechanical load on a surface of the workpiece, at least a portion of the thermomechanical load being a component of a cutting force, the component being applied in a direction normal to the surface of the workpiece. The first step of the method is to cool

the cutting tool to a second temperature lower than the first temperature before the cutting tool contacts the surface of the workpiece or while the workpiece is being machined. The second step is to reduce the component of the cutting force.

A first embodiment of the method for mitigating a detrimental effect of a thermomechanical load in a machined surface of a hard metal workpiece, the thermomechanical load being exerted on a surface of the workpiece by a hard cutting tool machining the workpiece, thereby forming the machined surface, includes cooling the machined surface by a cooling means having an initial temperature in a range of about -250°C to about +25°C.

There are several variations of the first embodiment of that method. In one variation, the cooling means includes at least one inert, water-free coolant. In another variation, the cooling means includes at least one stream containing a cryogenic fluid or at least one ice particle having a temperature less than about -75°C. In another variation, the hard metal workpiece includes an iron-containing alloy. In another variation, the hard cutting tool is made at least in part of a material selected from a group containing a ceramic compound; a ceramic-ceramic composite; a ceramic-metal composite; a diamond-like, metal-free material; an alumina-based ceramic; a cubic boron nitride-based ceramic material; a tungsten carbide-based material; and a cermet-type material.

A second embodiment of the method for mitigating the detrimental effect is similar to the first embodiment, but also includes cooling the cutting tool simultaneously by the cooling means.

In a third embodiment of the method for mitigating the detrimental effect, which is similar to the first embodiment, at least a portion of the thermomechanical load is a component of a cutting force, the component being applied in a direction normal to the surface of the workpiece. The method in this third embodiment includes reducing the component of the cutting force. In a variation of this embodiment, wherein the cutting tool has an inclination angle, the component of the cutting force is reduced by making the inclination angle more positive and the cooling means includes at least one stream containing a cryogenic fluid or at least one ice particle having a temperature less than about -75°C.

A fourth embodiment of the method for mitigating the detrimental effect is similar to the third embodiment, but includes cooling the cutting tool simultaneously by the cooling means. In a variation of the fourth embodiment, wherein the cutting tool has an inclination angle, the component of the cutting force is reduced by making the inclination angle more

positive and the cooling means includes at least one stream containing a cryogenic fluid with at least one ice particle having a temperature less than about -75°C.

Another aspect of the invention is a method for machining a hard metal workpiece. There are several embodiments of this method.

A first embodiment of the method for machining a hard metal workpiece, whereby a thickness of a thermomechanically-affected layer on an as-machined surface of the workpiece is reduced, the workpiece being machined with a hard cutting tool initially having a first temperature prior to contacting the surface of the workpiece, the hard cutting tool exerting a thermomechanical load on a surface of the workpiece, includes cooling the cutting tool to a second temperature lower than the first temperature before the cutting tool contacts the surface of the workpiece or while the workpiece is being machined.

A second embodiment of the method for machining a hard metal workpiece, whereby a detrimental effect of a thermomechanical load is mitigated in a machined surface of the workpiece, the thermomechanical load being exerted on a surface of the workpiece by a hard cutting tool forming the machined surface of the workpiece, includes cooling the machined surface by a cooling means having an initial temperature in a range of about -250°C to about +25°C.

A third embodiment of the method for machining a hard metal workpiece, whereby a thickness of a thermomechanically-affected layer on an as-machined surface of the workpiece is reduced, the workpiece being machined with a hard cutting tool, the hard cutting tool exerting a thermomechanical load on a surface of the workpiece, at least a portion of the thermomechanical load being a component of a cutting force, the component being applied in a direction normal to the surface of the workpiece, includes reducing the component of the cutting force.

In a fourth embodiment of the method for machining, which is similar to the first embodiment, at least a portion of thermomechanical load is a component of a cutting force, the component being applied in a direction normal to the surface of the workpiece. The fourth embodiment includes reducing the component of the cutting force.

A fifth embodiment of the method for machining is similar to the second embodiment, but includes cooling the cutting tool simultaneously by the cooling means.

In a sixth embodiment of the method for machining, which is similar to the second embodiment, at least a portion of the thermomechanical load is a component of the cutting force, the component being applied in a direction normal to the surface of the workpiece. The sixth embodiment includes reducing the component of the cutting force.

A seventh embodiment of the method for machining is similar to the sixth embodiment, but includes cooling the cutting tool simultaneously by the cooling means.

Another aspect of the invention is a workpiece machined by a method for machining as in any of the aforesaid embodiments and characterized by an improved surface or an improved property.

A first embodiment of the apparatus for reducing a thickness of a thermomechanically-affected layer on an as-machined surface of a hard metal workpiece being machined by a hard cutting tool exerting a thermomechanical load on a surface of the workpiece, includes a means for reducing the thermomechanical load.

There are several variations of the first embodiment of that apparatus. In one variation, the hard metal workpiece includes an iron-containing alloy. In another variation, the hard cutting tool is made at least in part of a material selected from a group containing a ceramic compound; a ceramic-ceramic composite; a ceramic-metal composite; a diamond-like, metal-free material; an alumina-based ceramic; a cubic boron nitride-based ceramic material; a tungsten carbide-based material; and a cermet-type material.

A second embodiment of the apparatus for reducing a thickness of a thermomechanically-affected layer on an as-machined surface of a hard metal workpiece being machined by a hard cutting tool initially having a first temperature prior to contacting the surface of the workpiece, the hard cutting tool exerting a thermomechanical load on a surface of the workpiece, at least a portion of the thermomechanical load being a component of a cutting force, the component being applied in a direction normal to the surface of the workpiece, includes: a means for cooling the cutting tool to a second temperature lower than the first temperature before the cutting tool contacts the surface of the workpiece or while the workpiece is being machined; and a means for reducing the component of the cutting force.

A first embodiment of the apparatus for mitigating a detrimental effect of a thermomechanical load in a machined surface of a hard metal workpiece, the thermomechanical load being exerted on a surface of the workpiece by a hard cutting tool machining the workpiece, thereby forming the machined surface, includes a means for cooling the machined surface by at least one stream of a coolant having an initial temperature in a range of about -250°C to about +25°C. In one variation of this embodiment, the stream contains at least one inert, water-free coolant. In another variation, the at least one stream contains a cryogenic fluid or at least one ice particle having a temperature less than about -75°C.

A second embodiment of the apparatus for mitigating a detrimental effect of a thermomechanical load in the machined surface of a hard metal workpiece, the thermomechanical load being exerted on a surface of the workpiece by a hard cutting tool machining the workpiece, thereby forming the machined surface, wherein at least a portion of the thermomechanical load is a component of the cutting force, the component being applied in a direction normal to the surface of the workpiece, includes: a means for cooling the machined surface by at least one stream containing at least one inert, water-free coolant having an initial temperature in a range of about -250°C to about +25°C; a means for cooling the cutting tool simultaneously by at least another stream containing at least one inert, water-free coolant; and a means for reducing the component of the cutting force.

Another aspect of the invention is an apparatus for machining a hard metal workpiece. There are several embodiments of the apparatus for machining.

A first embodiment of the apparatus for machining a hard metal workpiece, whereby a thickness of a thermomechanically-affected layer on an as-machined surface of the workpiece is reduced, the workpiece being machined by a hard cutting tool initially having a first temperature prior to contacting the surface of the workpiece, the hard cutting tool exerting a thermomechanical load on a surface of the workpiece, includes a means for cooling the cutting tool to a second temperature lower than the first temperature before the cutting tool contacts the surface of the workpiece or while the workpiece is being machined.

A second embodiment of the apparatus for machining a hard metal workpiece, whereby a detrimental effect of a thermomechanical load is mitigated in a machined surface of the workpiece, the thermomechanical load being exerted on a surface of the workpiece by a hard cutting tool forming the machined surface of the workpiece, includes a means for cooling the machined surface by a stream of a fluid having an initial temperature in a range of about -250°C to about +25°C.

A third embodiment of the apparatus for machining a hard metal workpiece, whereby a thickness of a thermomechanically-affected layer on an as-machined surface of the workpiece is reduced, the workpiece being machined by a hard cutting tool exerting a thermomechanical load on a surface of the workpiece, at least a portion of the thermomechanical load being a component of a cutting force, the component being applied in a direction normal to the surface of the workpiece, includes a means for reducing the component of the cutting force.

In a fourth embodiment, which is similar to the first embodiment, at least a portion of the thermomechanical load is a component of a cutting force, the component being

applied in a direction normal to the surface of the workpiece. The fourth embodiment includes a means for reducing the component of the cutting force.

The fifth embodiment of the apparatus for machining is similar to the second embodiment, but includes a means for simultaneously cooling the cutting tool with at least one other stream of the fluid, the means for cooling being means for spraying the streams of the fluid.

A sixth embodiment of the apparatus for machining is similar to the third embodiment, but includes a means for spraying the machined surface with at least one stream of a fluid having an initial temperature in a range of about -250°C to about +25°C.

The seventh embodiment of the apparatus for machining is similar to the sixth embodiment, but includes a means for spraying at least one other stream of the fluid simultaneously on the cutting tool.

Another aspect of the invention is a workpiece machined by an apparatus for machining as in any of the aforesaid embodiments and characterized by an improved surface or an improved property.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be described by way of example with reference to the accompanying drawings, in which:

Figure 1A is a schematic diagram illustrating an OD-hardturning operation using a solid barstock and a round cutting tool, plus a schematic representation of a detail illustrating a cross-sectional view of a typical subsurface microstructure of an as-machined workpiece;

Figure 1B is a schematic diagram illustrating an embodiment of the present invention used with an OD-hardturning operation similar to that shown in Figure 1A;

Figure 2 is a graph showing the measurement of white layer thickness for eight test conditions using different cutting speeds, cutting tool materials and cooling conditions;

Figure 3A is a graph showing the change of subsurface hardness as a result of hardturning with different cutting tool materials and cooling conditions at a cutting speed of 700 feet per minute;

Figure 3B is a graph showing the results of residual stress measurements on four types of samples as shown in Figure 3A;

Figure 4A is a schematic diagram illustrating a conventional method of hardturning where the inclination angle A-O-B is negative;

Figure 4B is a schematic diagram illustrating an embodiment of the present invention

wherein the inclination angle is increased from the negative value shown in Figure 4A to a positive value B-O-C shown in Figure 4B; and

Figure 4C is a schematic diagram illustrating another embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention involves machining hard metallic workpieces with hard cutting tools using a method which reduces the thickness of, or eliminates, thermomechanically-affected layers, including but not limited to white layer, and allows cutting at higher speeds without an excessive white layer using CBN tool materials, as well as less expensive Al_2O_3, carbide, cermet, or other hard tool materials. As used hereinafter, the term "white layer" refers to all types of "thermomechanically-affected layers," including but not limited to those associated with surface tensile stresses (*e.g.,* reduced fatigue-resistance, lower fracture toughness, and/or reduced wear resistance).

According to the present invention, the thermomechanical load exerted by the cutting tool at the machined surface is reduced using one or a combination of the three techniques (**A, B, C**) discussed below.

A. *Cooling cutting tool with a precisely aimed jet or spray of inert, water-free coolant, so that the heat transferred from the hot tool interface to the workpiece is reduced and, most preferably, the tool becomes a heat sink for the workpiece surface.*

The temperature of the tool cooling jet may vary between +25°C and –250°C, with the lower, cryogenic jet temperatures preferred. The tool cooled with such a jet makes the surface of a machined part colder. In addition, as observed during hard machining tests, in contrast to conventional machining technology teachings, the use of inert and water-free cooling jets enhances the life of Al_2O_3, CBN and other, hard cutting tools and, consequently, allows the use of sharper cutting edges which generate lower cutting forces and thinner white layers.

B. *Cooling the as-formed or as-machined workpiece surface with the same type of direct impinging cooling jet or spray as in technique A.*

Based on observations, it appears that cooling of the as-machined workpiece surface reduces the depth of heat penetration into machined material and, consequently, the extent of undesired material transformations. The surface-cooling jet of technique **B** may be separate from the tool-cooling jet of technique **A**; or just a single jet can be aimed

in such a way that it cools both the tool and the surface simultaneously. Persons skilled in the art will recognize that multiple cooling jets or sprays of technique **A** and technique **B** could be used according to the present invention.

C. *Reducing the cutting force component in the direction normal to the as-machined workpiece surface.*

As observed during tests, the cutting force component normal to the as-machined workpiece surface appears to be a significant source of heat flux entering the surface and generating white layer. In the case of the most frequently practiced OD-hardturning operations, where the normal force is the radial force, a more positive tool inclination angle results in a reduced thermomechanical load entering the surface. In the case of orthogonal cutting, where the normal force is the feed force, a more positive rake angle will be more important. In the most generic cutting case, both the inclination angle and the rake angle are made more positive than the conventional, negative values that are used in current hard machining operations. Since the life of hard cutting tools scales inversely with the positive inclination and rake angle, the increase in the value of these angles is most advantageous if practiced in combination with technique **A**, which also enhances tool life during hard machining.

Figure 1A is a schematic diagram of an OD-hardturning operation involving a solid barstock as the workpiece 12 and a round cutting tool 14 (with a cutting insert marked as CT) viewed from the topside of the tool rake surface. This view is referred to as the X-Z plane view. The X-Z projection of the major cutting forces that have to be applied to the workpiece via the cutting tool is denoted as F_{xz}feed or feed force, and F_{xz}radial or radial force, where the feed force is less than the radial force. The location of the thermomechanically-affected layers 16 on the as-machined surface of the workpiece is illustrated in Figure 1A. The detail on the right of the figure shows a cross-sectional view of the typical subsurface microstructure of the as-machined workpiece that can be observed under a scanning electron microscope (SEM) using magnifications ranging from 3,000 to 12,000 times. The following designations are used: OS – outer surface that was in direct contact with the cutting tool during hardturning, WL – white layer, DL – dark layer, and BM – base metal representing the parent or unaffected structure of the barstock.

Based on SEM examinations carried out on a popular bearing steel grade, AISI 52100 (1wt%C and 1.5wt%Cr), hardened to 61 Rockwell on scale C and hard machined, the white layer (WL) is a thin band of poorly etching material with broadly dispersed, spherical carbides. The underlying dark layer (DL) is thicker than the white layer, and

contains more and bigger carbide particles, as well as microfeatures suggesting martensitic needles and latches. The thermomechanically-affected layer includes both the white layer (WL) and the dark layer (DL) but also extends even deeper into the base metal and cannot be measured using simple microscopic methods. Consequently, the evaluation of the thickness of a thermomechanically-affected layer is usually based on (1) a microscopic measurement of the well contrasting white layer (WL), combined with (2) additional measurements of the mechanical properties of the material below the as-machined surface, *e.g.*, residual stress and microhardness measurements.

Figure 1B shows the same X-Z view of the cutting tool 14 and the workpiece 12 (barstock), but does not include the cross-sectional details of the subsurface microstructure as in Figure 1A. Points $CJ_{xz}1$ and $CJ_{xz}2$ are X-Z plane projections of the preferred locations of cold jet-discharging orifices (not shown) that aim the cooling jets (18, 20) at the rake of the cutting tool, at the as-machined surface of the workpiece and, optionally, into the clearance gap between the cutting tool and the workpiece surface, just below the rake surface and the cutting tool-workpiece contact area. Thus, the cold jet impact is limited to the cutting tool and the as-machined workpiece surface area. It is important not to cool the barstock upstream of the cutting tool, since such cooling increases the mechanical energy required for cutting, *i.e.*, cancels the cooling effect and simultaneously shortens the life of the cutting tool. As shown in Figure 1B, the $CJ_{xz}1$ jet may be positioned higher or lower, above the rake along the Y-axis, and may impact only the rake surface along the contact length. This represents technique **A**, discussed earlier. Alternatively, the $CJ_{xz}1$ jet may spray both the rake and the as-machined surface downstream of the cutting tool. This alternate approach combines techniques **A** and **B**. The $CJ_{xz}2$ jet may be positioned behind or below the cutting tool, along the Y and the Z axes, in order to work according to technique **B**. The $CJ_{xz}2$ jet can be eliminated as well if the spray 18 from the $CJ_{xz}1$ jet is sufficiently effective in cooling the machined surface. The results of comparative tests carried out to evaluate the effectiveness of techniques **A**, **B**, and **C** are summarized in Table 1, which details the conditions of the tests.

TABLE 1

Cutting tool system	Cutting insert:	CBN, a "low-content PCBN" type	Al_2O_3-based ceramic type, Al_2O_3-TiCN composition
	Insert designation and description:	BNC80, 4NC-CNMA432, 4 cutting edges, PVD-TiN coated	KY4400, CNGA432, 4 cutting edges, PVD-TiN coated
	Supplier/toolmaker:	Sumitomo	Kennametal
	Edge chamfer angle, measured:	25° +/- 3°	25° +/- 3°
	Chamfer width, measured:	0.00325 inches	0.00425 inches
	Toolholder for cutting insert:	MCLNL-164C, Kennametal	MCLNL-164C, Kennametal
	Toolholder's angles:	-5° rake angle and –5° inclination angle	-5° rake angle and –5° inclination angle
Cutting parameters	Cutting speed in ft/minute:	400 and 700	400 and 700
	Feedrate in inches/revolution, see: comment (1) below	0.004	0.004
	Depth of cut in inches:	0.015	0.015
	Cutting (feed) direction:	Radial (along X-axis), facing	Radial (along X-axis), facing
Cooling conditions	Two cooling methods:	(1) Dry (no cooling), and (2) $CJ_{xz}1$ jet aimed at the tool rake and at as-machined surface according to techniques A and B	(1) Dry (no cooling), and (2) $CJ_{xz}1$ jet aimed at the tool rake and at as-machined surface according to techniques A and B
	Cooling medium for case (2), above:	Cryogenic liquid nitrogen jet impacting rake and as-machined surface in form of a 2-phase fluid which is boiling at –197°C	Cryogenic liquid nitrogen jet impacting rake and as-machined surface in form of a 2-phase fluid which is boiling at –197°C
Workpiece material	AISI 52100 bearing steel, 1.0wt% carbon, 1.5wt% chromium	Oil quenched and low-tempered to 61 HRC +/- 1 HRC	Oil quenched and low-tempered to 61 HRC +/- 1 HRC

White layer examination conditions	Workpiece material volume removed by a new cutting edge before taking as-machined workpiece surface samples for examination of white layer, see comment (2) below	1.06 cubic inches	1.06 cubic inches
	Number of interruptions during workpiece material cutting prior to white layer examination:	8	8
	Surface roughness range of as-machined workpiece surface samples transferred for white layer evaluations	Ra = 15-20 microinches/inch	Ra = 15-30 microinches/inch
	Residual stress measurement method:	Incremental hole drilling with 1 mm diameter drill, extensometer rosette	Incremental hole drilling with 1 mm diameter drill, extensometer rosette
	Direction of metallographic cut for image evaluation and microhardness measurements:	Perpendicular to as-machined workpiece surface and in the radial direction (along X-axis)	Perpendicular to as-machined workpiece surface and in the radial direction (along X-axis)
	Microhardness measurement method – Knoop, 100G load applied for 15 seconds	Profiling hardness as a function of depth under as-machined workpiece surface with blade-shaped indenter	Profiling hardness as a function of depth under as-machined workpiece surface with blade-shaped indenter
	Etchant used for developing white layer contrast on cross-sectional metallographic samples of as-machined workpiece surface:	Nital – 5% HNO_3 in ethanol applied to sample surface for 10 seconds	Nital – 5% HNO_3 in ethanol applied to sample surface for 10 seconds

Comments	(1) Since the feedrate was larger than the chamfer width of the CBN tool used, the effective rake angle of the CBN tool was larger, i.e. more positive or sharper, than the effective rake angle of the Al_2O_3 tool. Consequently, the CBN insert used generated lower normal force during face cutting than the Al_2O_3 insert which, according to technique **C** results in a lower thermomechanical load at as-machined work surface, i.e. a thinner thermomechanically-affected surface including white layer. The 2nd factor influencing white layer is the temperature at the tool-work contact area. Thermal conductivity of the low-PCBN tool is somewhat higher than that of the Al_2O_3-TiCN tool which means the contact area is cooler in the former case. (2) The procedure of removing initial material volume with cutting edge prior to taking as-machined workpiece surface samples replicates typical industrial hard machining conditions where the majority of part is produced using somewhat worn cutting edges.

Figure 2 shows the results of SEM measurements of the white layer thickness for eight (8) test conditions. The results show that the sharper and more conductive CBN tool tends to produce a thinner white layer than that produced by the Al_2O_3 tool. The reduction of the normal component of the cutting force coming with the sharper tools, and the reduction of tool temperature with more conductive tool materials, are consistent with our techniques **A** and **C**. However, the most significant factor in reducing white layer thickness was the cooling jet applied according to techniques **A** and **B**, which was capable of reducing the white layer by about 40% regardless of the tool and cutting speed used. The most important and surprising finding is that the white layer produced with the jet-cooled Al_2O_3 tool is significantly thinner than the white layer produced by the CBN tool operated the conventional way (*i.e.,* dry). Moreover, the white layer produced with the Al_2O_3 tool at 700 feet/minute is thinner than the white layer produced with the dry CBN tool at 400 ft/minute. Thus, the present invention enables hard machining operators to produce better parts faster and at lower tooling cost.

Figure 3A shows the change of subsurface hardness as a result of hardturning with the CBN and Al_2O_3 tools at the cutting speed of 700 feet/minute. Undesired softening of workpiece material observed within the first 15 micrometers under the as-machined surface after the conventional dry hardturning is prevented when the cryogenic cooling jet is used according to techniques **A** and **B** of the invention.

Figure 3B plots results of residual stress measurements on the same four types of samples as in Figure 3A. In the case of Al_2O_3, the cryojet cooling eliminates a steep tensile stress resulting from the conventional dry hardturning. In the case of CBN, the cryojet makes the subsurface stress slightly more compressive and, just as in the case of Al_2O_3, flattens the fluctuation of stress with depth. Both Figures 3A and 3B show that the techniques **A** and **B** of the invention bring an unexpected improvement in the mechanical properties of a hard machined surface.

As Figure 1B presented the X-Z plane view of OD-hardturning, Figures 4A, 4B and 4C present the same operation but in the X-Y plane showing a section of the face of the barstock or workpiece 12 and the side of the cutting insert (CT). Figure 4A shows the conventional method of hardturning where the inclination angle A-O-B is negative. The X-Y projection of the work-material reaction force that resists machining operation, R_{xy}mach, can be presented with some degree of simplification as a sum of two forces projected on the same plane X-Y: tangential reaction cutting force, R_{xy}tan, and radial reaction force, R_{xy}rad. The radial reaction force is larger than zero, usually larger than the tangential or the feed force (extending along the Z-axis), and in some hardturning cases larger than the tangential and feed forces combined. To balance the radial reaction force, the radial force applied via the cutting tool to the workpiece surface, F_{xz}rad, must be equally large, which leads to a high thermomechanical load being applied by the cutting tool to the workpiece surface and contributes to the formation of thick white layers.

Figure 4B presents a modification of the conventional cutting geometry (in Figure 4A) as the inclination angle, B-O-C, is increased from the initial negative value (represented by A-O-B) in Figure 4A to a new positive value, which results in reversing the direction of the radial reaction force, R_{xy}rad. In effect, the increased or more positive inclination angle reduces the required radial force of the cutting tool to zero or below zero, resulting in a reduction of the thermomechanically-affected layer at the workpiece surface. This modification of the cutting geometry represents technique **C** of the present invention. This technique may be extended to hard facing and hard orthogonal cutting operations where, if effective rake angles are made more positive than the conventionally used negative angles, then the thermomechanical load at the workpiece surface is reduced, and the thermomechanically-affected layer is thinner.

The increased inclination and/or rake angles may produce tensile stresses around the cutting edges of typically brittle tools used in hard machining. Such tensile stresses may lead to premature tool failures in the case of the conventional technology that teaches dry cutting conditions. As observed, the failures are less frequent and tool life is extended when at least one cooling jet or spray is aimed at the rake of the cutting tool during hard machining, and the cooling fluid used is inert, water-free, and preferably cryogenic. (The term "inert" means that the cooling fluid does not react with the hard metal and does not degrade the mechanical properties of the hard metal or the hard cutting tool.)

Figure 4C shows the X-Y plane projection of two cooling jets, $CJ_{xy}1$ and $CJ_{xy}2$, corresponding to the jets shown in Figure 1B in the X-Z plane view. The application of

technique **C** is most advantageous from the production and cost standpoint, when CJ1 or, alternatively, CJ1 and CJ2 are spraying coolant during the hard cutting, as shown in Figure 4C.

The present invention minimizes detrimental white layer and other thermomechanically-affected layers in an as-machined workpiece surface by reducing the thermomechanical load exerted by the cutting tool on the workpiece material surface during hard machining. As discussed above, the present invention includes three techniques (A, B, C) which may be used separately or in combination (AB, AC, BC, ABC).

Although illustrated and described herein with reference to certain specific embodiments, the present invention is nevertheless not intended to be limited to the details shown. Rather, various modifications may be made in the details within the scope and range of equivalents of the claims and without departing from the spirit of the invention.

CLAIMS

1. A method for reducing a thickness of a thermomechanically-affected layer on an as-machined surface of a hard metal workpiece being machined by a hard cutting tool exerting a thermomechanical load on a surface of the workpiece, comprising reducing the thermomechanical load.

2. A method as in claim 1, wherein the cutting tool initially has a first temperature prior to contacting the surface of the workpiece, and wherein the thermomechanical load is reduced by cooling the cutting tool to a second temperature lower than the first temperature before the cutting tool contacts the surface of the workpiece or while the workpiece is being machined.

3. A method as in claim 2, wherein the cutting tool is cooled by an external cooling means.

4. A method as in claim 3, wherein the cooling means comprises at least one inert, water-free coolant.

5. A method as in claim 3, wherein the cooling means comprises at least one cryogenic fluid.

6. A method as in claim 1, wherein at least a portion of the thermomechanical load is a component of a cutting force, the component being applied in a direction normal to the surface of the workpiece, and wherein the thermomechanical load is reduced by reducing the component of the cutting force.

7. A method as in claim 6, wherein the cutting tool has an inclination angle, and wherein the component of the cutting force is reduced by making the inclination angle more positive.

8. A method as in claim 6, wherein the cutting tool has a rake angle, and wherein the component of the cutting force is reduced by making the rake angle more positive.

9. A method as in claim 4, wherein the cutting tool has a hardness and a resistance to cracking, and wherein cooling the cutting tool with the cooling means results in an increase in the hardness or an increase in the resistance to cracking.

10. A method as in claim 1, wherein the hard metal workpiece comprises an iron-containing alloy.

11. A method as in claim 1, wherein the hard cutting tool is made at least in part of a material selected from a group containing a ceramic compound; a ceramic-ceramic composite; a ceramic-metal composite; a diamond-like, metal-free material; an alumina-based ceramic; a cubic boron nitride-based ceramic material; a tungsten carbide-based material; and a cermet-type material.

12. A method for reducing a thickness of a thermomechanically-affected layer on an as-machined surface of a hard metal workpiece being machined by a hard cutting tool initially having a first temperature prior to contacting the surface of the workpiece, the hard cutting tool exerting a thermomechanical load on a surface of the workpiece, at least a portion of the thermomechanical load being a component of a cutting force, the component being applied in a direction normal to the surface of the workpiece, comprising the steps of:

cooling the cutting tool to a second temperature lower than the first temperature before the cutting tool contacts the surface of the workpiece or while the workpiece is being machined; and

reducing the component of the cutting force.

13. A method for mitigating a detrimental effect of a thermomechanical load in a machined surface of a hard metal workpiece, the thermomechanical load being exerted on a surface of the workpiece by a hard cutting tool machining the workpiece, thereby forming the machined surface, comprising cooling the machined surface by a cooling means having an initial temperature in a range of about -250°C to about +25°C.

14. A method as in claim 13, wherein the cooling means comprises at least one stream containing a cryogenic fluid or at least one ice particle having a temperature less than about -75°C.

15. A method as in claim 13, wherein the cooling means comprises at least one inert, water-free coolant.

16. A method as in claim 13, wherein the hard metal workpiece comprises an iron-containing alloy.

17. A method as in claim 13, wherein the hard cutting tool is made at least in part of a material selected from a group containing a ceramic compound; a ceramic-ceramic composite; a ceramic-metal composite; a diamond-like, metal-free material; an alumina-based ceramic; a cubic boron nitride-based ceramic material; a tungsten carbide-based material; and a cermet-type material.

18. A method for mitigating a detrimental effect of a thermomechanical load in a machined surface of a hard metal workpiece, the thermomechanical load being exerted on a surface of the workpiece by a hard cutting tool machining the workpiece, thereby forming the machined surface, comprising the steps of:

cooling the machined surface by a cooling means having an initial temperature in a range of about -250°C to about +25°C; and

cooling the cutting tool simultaneously by the cooling means.

19. A method for mitigating a detrimental effect of a thermomechanical load in a machined surface of a hard metal workpiece, the thermomechanical load being exerted on a surface of the workpiece by a hard cutting tool machining the workpiece, thereby forming the machined surface, wherein at least a portion of the thermomechanical load is a component of a cutting force, the component being applied in a direction normal to the surface of the workpiece, comprising the steps of:

cooling the machined surface by a cooling means having an initial temperature in a range of about -250°C to about +25°C; and

reducing the component of the cutting force.

20. A method as claim 19 wherein the cutting tool has an inclination angle, and wherein the component of the cutting force is reduced by making the inclination angle more positive and the cooling means comprises at least one stream containing a cryogenic fluid or at least one ice particle having a temperature less than about -75°C.

21. A method for mitigating a detrimental effect of a thermomechanical load in a machined surface of a hard metal workpiece, the thermomechanical load being exerted on a surface of the workpiece by a hard cutting tool machining the workpiece, thereby forming the machined surface, wherein at least a portion of the thermomechanical load is a component of the cutting force, the component being applied in a direction normal to the surface of the workpiece, comprising the steps of:

cooling the machined surface by a cooling means having an initial temperature in a range of about -250°C to about +25°C;

cooling the cutting tool simultaneously by the cooling means; and

reducing the component of the cutting force.

22. A method as in claim 21, wherein the cutting tool has an inclination angle, and wherein the component of the cutting force is reduced by making the inclination angle more positive and the cooling means comprises at least one stream containing a cryogenic fluid with at least one ice particle having a temperature less than about -75°C.

23. A method for machining a hard metal workpiece, whereby a thickness of a thermomechanically-affected layer on an as-machined surface of the workpiece is reduced, the workpiece being machined with a hard cutting tool initially having a first temperature prior to contacting the surface of the workpiece, the hard cutting tool exerting a thermomechanical load on a surface of the workpiece, comprising cooling the cutting tool to a second temperature lower than the first temperature before the cutting tool contacts the surface of the workpiece or while the workpiece is being machined.

24. A workpiece machined by a method as in claim 23 and characterized by an improved surface or an improved property.

25. A method for machining a hard metal workpiece, whereby a detrimental effect of a thermomechanical load is mitigated in a machined surface of the workpiece, the thermomechanical load being exerted on a surface of the workpiece by a hard cutting tool forming the machined surface of the workpiece, comprising cooling the machined surface by a cooling means having an initial temperature in a range of about -250°C to about +25°C.

26. A workpiece machined by a method as in claim 25 and characterized by an improved surface or an improved property.

27. A method for machining a hard metal workpiece, whereby a thickness of a thermomechanically-affected layer on an as-machined surface of the workpiece is reduced, the workpiece being machined with a hard cutting tool, the hard cutting tool exerting a thermomechanical load on a surface of the workpiece, at least a portion of the thermomechanical load being a component of a cutting force, the component being applied in a direction normal to the surface of the workpiece, comprising reducing the component of the cutting force.

28. A workpiece machined by a method as in claim 27 and characterized by an improved surface or an improved property.

29. A method for machining a hard metal workpiece, whereby a thickness of a thermomechanically-affected layer on an as-machined surface of the workpiece is reduced, the workpiece being machined with a hard cutting tool initially having a first temperature prior to contacting the surface of the workpiece, the hard cutting tool exerting a thermomechanical load on a surface of the workpiece, at least a portion of the thermomechanical load being a component of a cutting force, the component being applied in a direction normal to the surface of the workpiece, comprising the steps of:

cooling the cutting tool to a second temperature lower than the first temperature before the cutting tool contacts the surface of the workpiece or while the workpiece is being machined; and

reducing the component of the cutting force.

30. A method for machining a hard metal workpiece, whereby a detrimental effect of a thermomechanical load is mitigated in a machined surface of the workpiece, the thermomechanical load being exerted on a surface of the workpiece by a hard cutting tool forming the machined surface of the workpiece, comprising the steps of:

cooling the machined surface by a cooling means having an initial temperature in a range of about -250°C to about +25°C; and

cooling the cutting tool simultaneously by the cooling means.

31. A method for machining a hard metal workpiece, whereby a detrimental effect of a thermomechanical load is mitigated in a machined surface of the workpiece, the thermomechanical load being exerted on a surface of the workpiece by a hard cutting tool forming the machined surface of the workpiece, wherein at least a portion of the thermomechanical load is a component of a cutting force, the component being applied in a direction normal to the surface of the workpiece, comprising the steps of:

cooling the machined surface by a cooling means having an initial temperature in a range of about -250°C to about +25°C; and

reducing the component of the cutting force.

32. A method for machining a hard metal workpiece, whereby a detrimental effect of a thermomechanical load is mitigated in a machined surface of the workpiece, the thermomechanical load being exerted on a surface of the workpiece by a hard cutting tool forming the machined surface of the workpiece, wherein at least a portion of the thermomechanical load is a component of a cutting force, the component being applied in a direction normal to the surface of the workpiece, comprising the steps of:

cooling the machined surface by a cooling means having an initial temperature having a range of about -250°C to about +25°C;

cooling the cutting tool simultaneously by the cooling means; and

reducing the component of the cutting force.

33. An apparatus for reducing a thickness of a thermomechanically-affected layer on an as-machined surface of a hard metal workpiece being machined by a hard cutting tool exerting a thermomechanical load on a surface of the workpiece, comprising a means for reducing the thermomechanical load.

34. An apparatus as in claim 33, wherein the hard metal workpiece comprises an iron-containing alloy.

35. An apparatus as in claim 33, wherein the hard cutting tool is made at least in part of a material selected from a group containing a ceramic compound; a ceramic-ceramic composite; a ceramic-metal composite; a diamond-like, metal-free material; an alumina-based ceramic; a cubic boron nitride-based ceramic material; a tungsten carbide-based material; and a cermet-type material.

36. An apparatus for reducing a thickness of a thermomechanically-affected layer on an as-machined surface of a hard metal workpiece being machined by a hard cutting tool initially having a first temperature prior to contacting the surface of the workpiece, the hard cutting tool exerting a thermomechanical load on a surface of the workpiece, at least a portion of the thermomechanical load being a component of a cutting force, the component being applied in a direction normal to the surface of the workpiece, comprising:

a means for cooling the cutting tool to a second temperature lower than the first temperature before the cutting tool contacts the surface of the workpiece or while the workpiece is being machined; and

a means for reducing the component of the cutting force.

37. An apparatus for mitigating a detrimental effect of a thermomechanical load in a machined surface of a hard metal workpiece, the thermomechanical load being exerted on a surface of the workpiece by a hard cutting tool machining the workpiece, thereby forming the machined surface, comprising a means for cooling the machined surface by at least one stream of a coolant having an initial temperature in a range of about -250°C to about +25°C.

38. An apparatus as in claim 37, wherein the at least one stream contains a cryogenic fluid or at least one ice particle having a temperature less than about -75°C.

39. An apparatus as in claim 37, wherein the stream contains at least one inert, water-free coolant.

40. An apparatus for mitigating a detrimental effect of a thermomechanical load in the machined surface of a hard metal workpiece, the thermomechanical load being exerted on a surface of the workpiece by a hard cutting tool machining the workpiece, thereby forming the machined surface, wherein at least a portion of the thermomechanical load is a component of the cutting force, the component being applied in a direction normal to the surface of the workpiece, comprising:

a means for cooling the machined surface by at least one stream containing at least one inert, water-free coolant having an initial temperature in a range of about -250°C to about +25°C;

a means for cooling the cutting tool simultaneously by at least another stream containing at least one inert, water-free coolant; and

a means for reducing the component of the cutting force.

41. An apparatus for machining a hard metal workpiece, whereby a thickness of a thermomechanically-affected layer on an as-machined surface of the workpiece is reduced, the workpiece being machined by a hard cutting tool initially having a first temperature prior to contacting the surface of the workpiece, the hard cutting tool exerting a thermomechanical load on a surface of the workpiece, comprising a means for cooling the cutting tool to a second temperature lower than the first temperature before the cutting tool contacts the surface of the workpiece or while the workpiece is being machined.

42. A workpiece machined by an apparatus as in claim 41 and characterized by an improved surface or an improved property.

43. An apparatus for machining a hard metal workpiece, whereby a detrimental effect of a thermomechanical load is mitigated in a machined surface of the workpiece, the thermomechanical load being exerted on a surface of the workpiece by a hard cutting tool forming the machined surface of the workpiece, comprising a means for cooling the machined surface by a stream of a fluid having an initial temperature in a range of about -250°C to about +25°C.

44. A workpiece machined by an apparatus as in claim 43 and characterized by an improved surface or an improved property.

45. An apparatus for machining a hard metal workpiece, whereby a thickness of a thermomechanically-affected layer on an as-machined surface of the workpiece is reduced, the workpiece being machined by a hard cutting tool exerting a thermomechanical load on a surface of the workpiece, at least a portion of the thermomechanical load being a component of a cutting force, the component being applied in a direction normal to the surface of the workpiece, comprising a means for reducing the component of the cutting force.

46. A workpiece machined by an apparatus as in claim 45 and characterized by an improved surface or an improved property.

47. An apparatus for machining a hard metal workpiece, whereby a thickness of a thermomechanically-affected layer on an as-machined surface of the

workpiece is reduced, the workpiece being machined by a hard cutting tool initially having a first temperature prior to contacting the surface of the workpiece, the hard cutting tool exerting a thermomechanical load on a surface of the workpiece, at least a portion of the thermomechanical load being a component of a cutting force, the component being applied in a direction normal to the surface of the workpiece, comprising:

a means for cooling the cutting tool to a second temperature lower than the first temperature before the cutting tool contacts the surface of the workpiece or while the workpiece is being machined; and

a means for reducing the component of the cutting force.

48. An apparatus for machining a hard metal workpiece, whereby a detrimental effect of a thermomechanical load is mitigated in a machined surface of the workpiece, the thermomechanical load being exerted on a surface of the workpiece by a hard cutting tool forming the machined surface of the workpiece, comprising:

a means for spraying the machined surface with at least one stream of a fluid having an initial temperature in a range of about -250°C to about +25°C; and

a means for spraying at least one other stream of the fluid simultaneously on the cutting tool.

49. An apparatus for machining a hard metal workpiece, whereby a detrimental effect of a thermomechanical load is mitigated in a machined surface of the workpiece, the thermomechanical load being exerted on a surface of the workpiece by a hard cutting tool forming the machined surface of the workpiece, wherein at least a portion of the thermomechanical load is a component of a cutting force, the component being applied in a direction normal to the surface of the workpiece, comprising:

a means for spraying the machined surface with at least one stream of a fluid having an initial temperature in a range of about -250°C to about +25°C; and

a means for reducing the component of the cutting force.

50. An apparatus for machining a hard metal workpiece, whereby a detrimental effect of a thermomechanical load is mitigated in a machined surface of the workpiece, the thermomechanical load being exerted on a surface of the workpiece by a hard cutting tool forming the machined surface of the workpiece, wherein at least a portion of the thermomechanical load is a component of a cutting force, the component being applied in a direction normal to the surface of the workpiece, comprising:

a means for spraying the machined surface with at least one stream of a fluid having an initial temperature in a range of about -250°C to about +25°C;

a means for spraying at least one other stream of the fluid simultaneously on the cutting tool; and

a means for reducing the component of the cutting force.

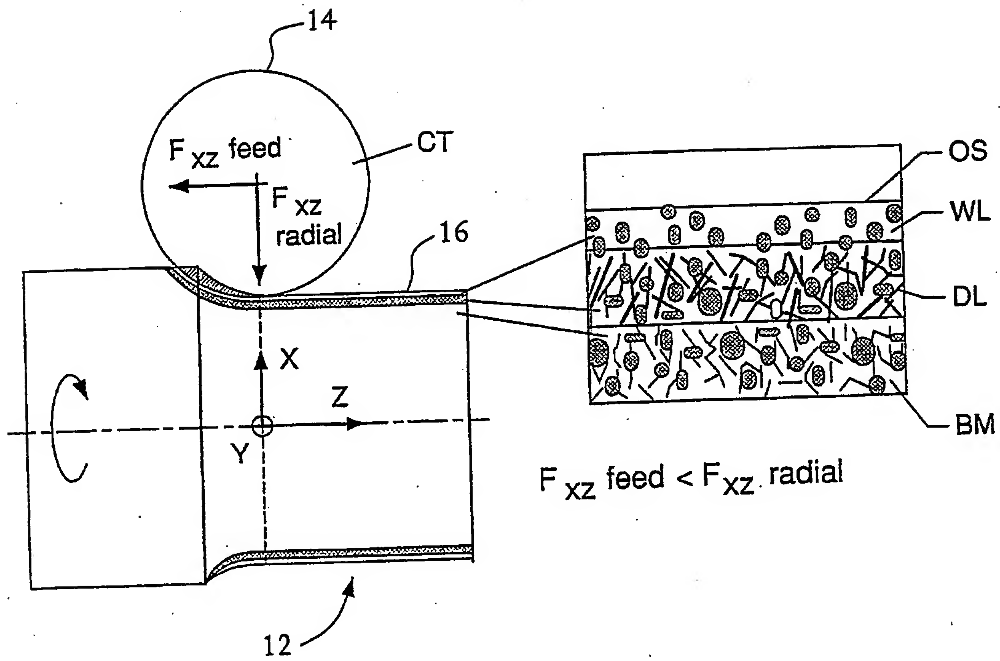
14
F_{xz} feed
CT
F_{xz} radial
16
OS
WL
DL
BM
X
Z
Y
F_{xz} feed < F_{xz} radial
12

FIG. 1A

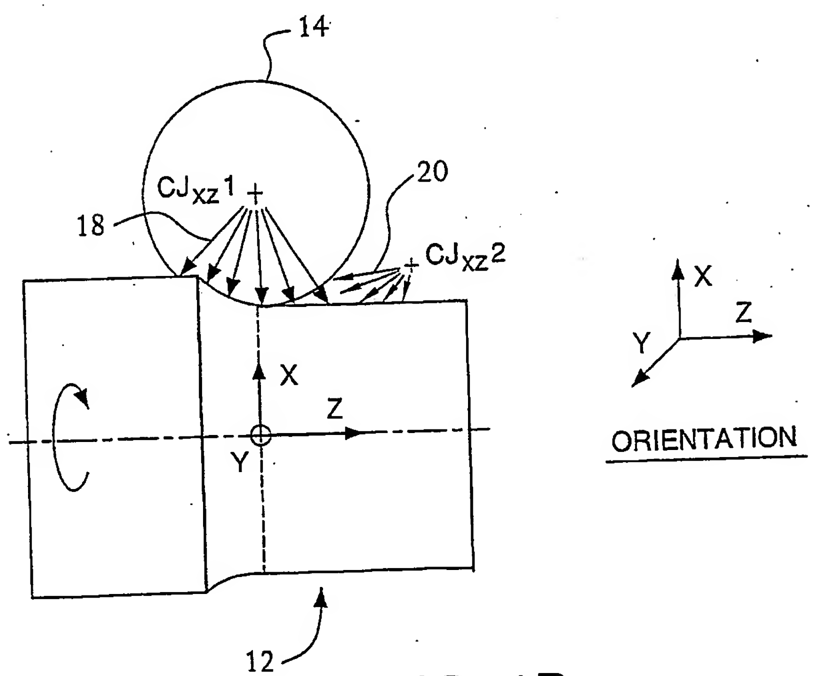
14
$CJ_{xz}1$
20
18
$CJ_{xz}2$
X
Z
Y
X
Z
Y
ORIENTATION
12

FIG. 1B

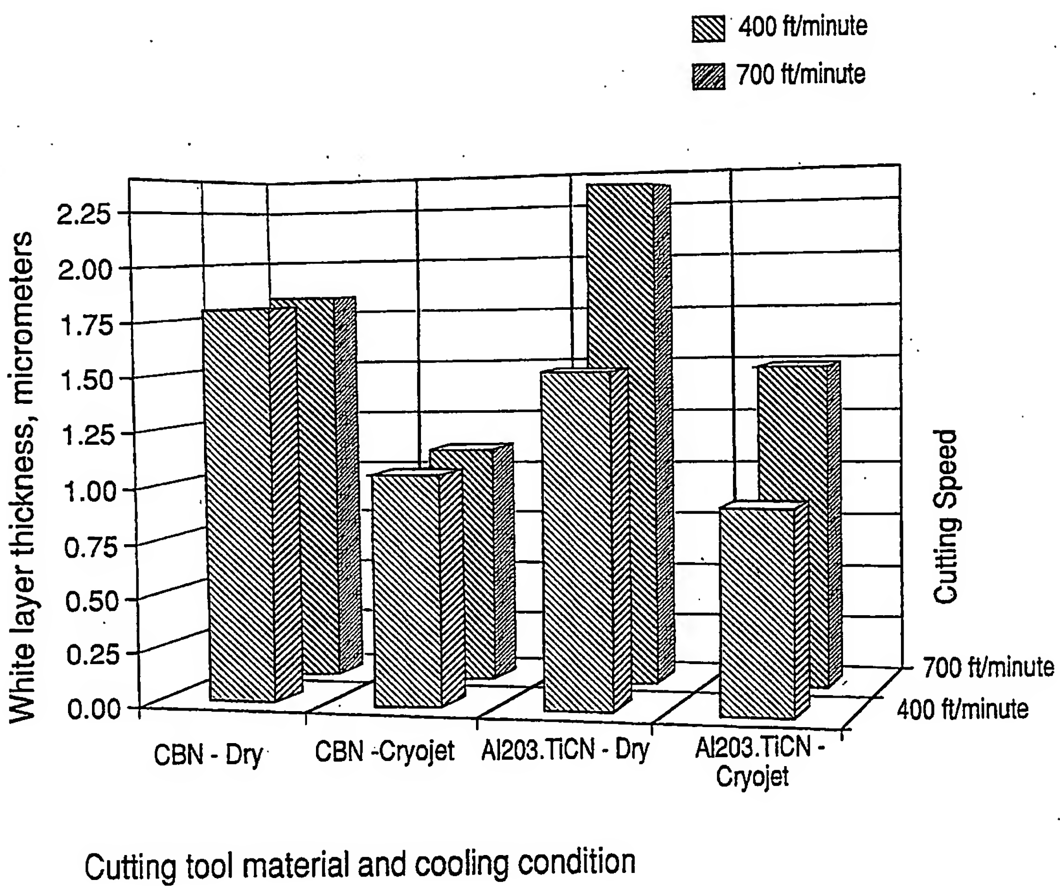
400 ft/minute
700 ft/minute
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
White layer thickness, micrometers
Cutting Speed
700 ft/minute
400 ft/minute
CBN - Dry
CBN -Cryojet
Al203.TiCN - Dry
Al203.TiCN - Cryojet
Cutting tool material and cooling condition

FIG. 2

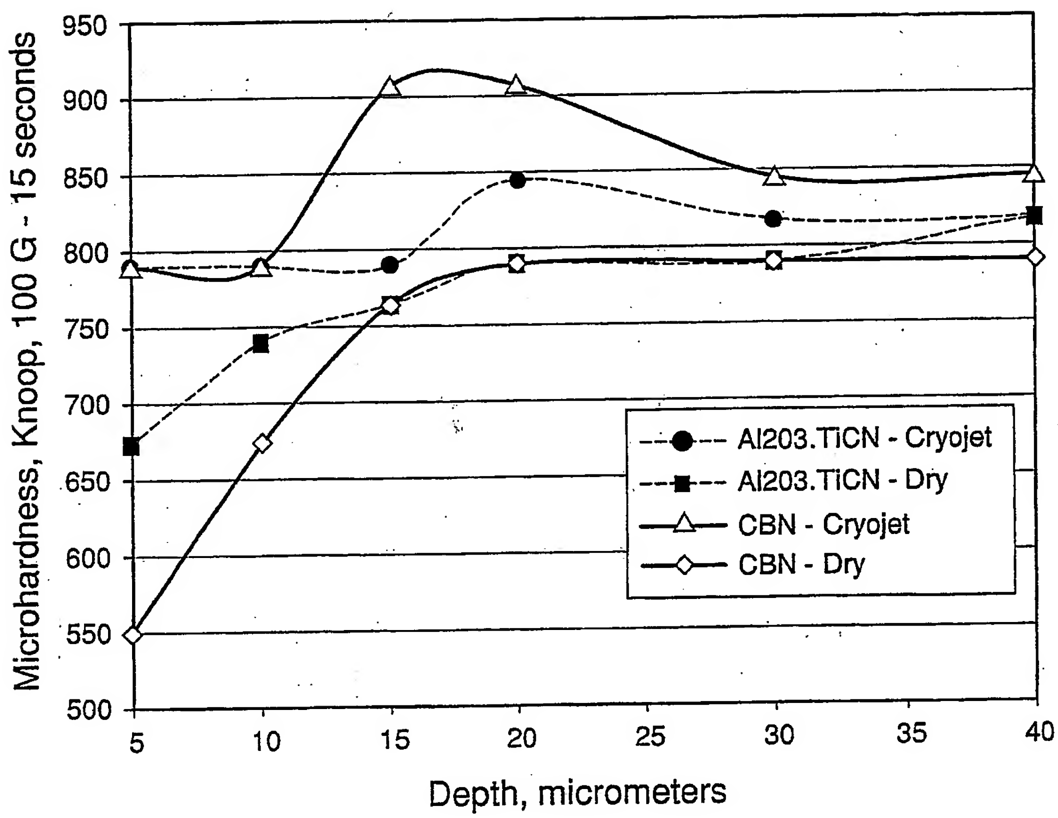
950
900
850
800
750
700
650
600
550
500
Microhardness, Knoop, 100 G - 15 seconds
5
10
15
20
25
30
35
40
Depth, micrometers
Al203.TiCN - Cryojet
Al203.TiCN - Dry
CBN - Cryojet
CBN - Dry

FIG. 3A

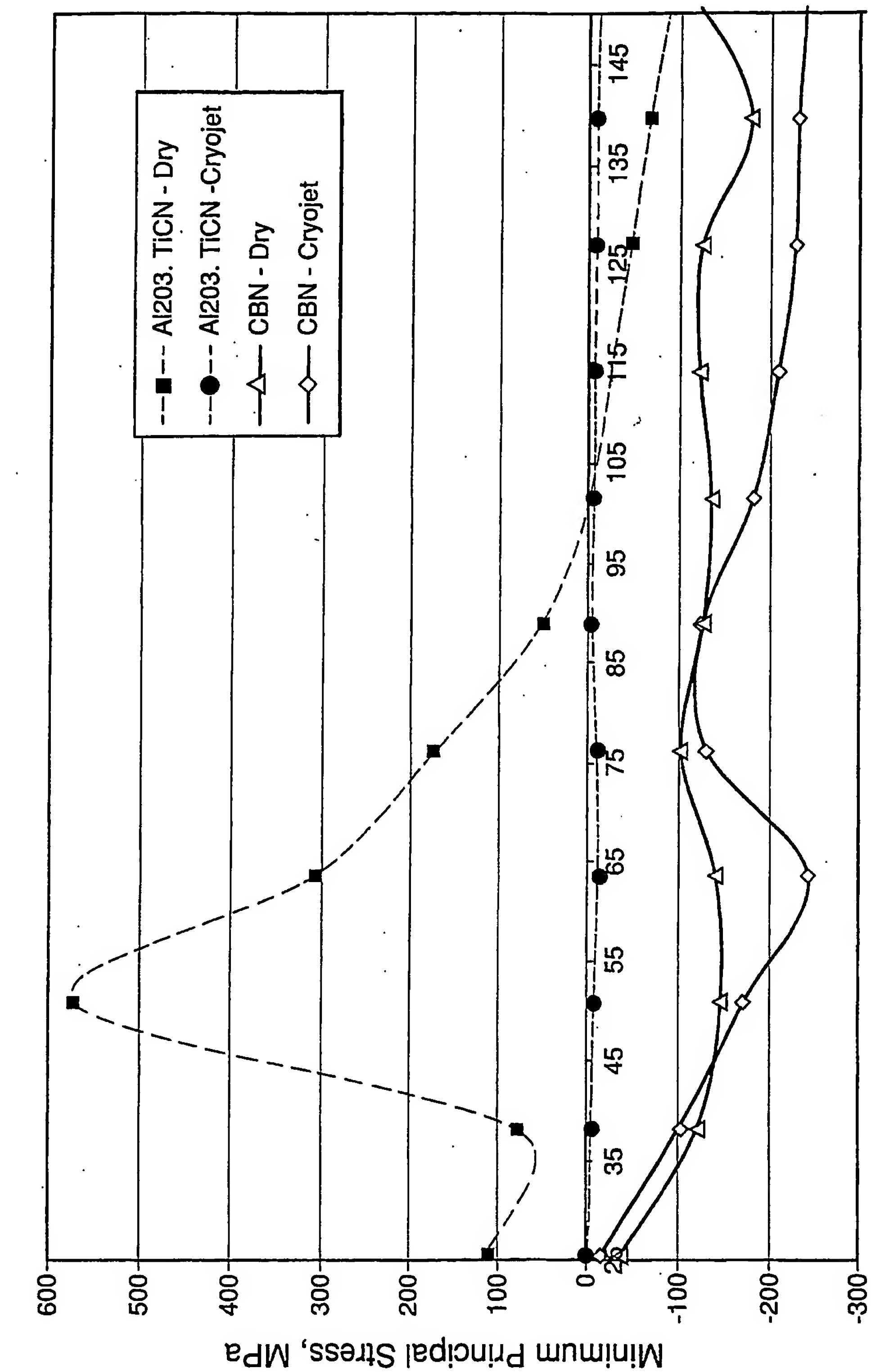
Al203. TiCN - Dry
Al203. TiCN -Cryojet
CBN - Dry
CBN - Cryojet
Minimum Principal Stress, MPa
600
500
400
300
200
100
0
-100
-200
-300
Depth, micrometers
35
45
55
65
75
85
95
105
115
125
135
145

FIG. 3B

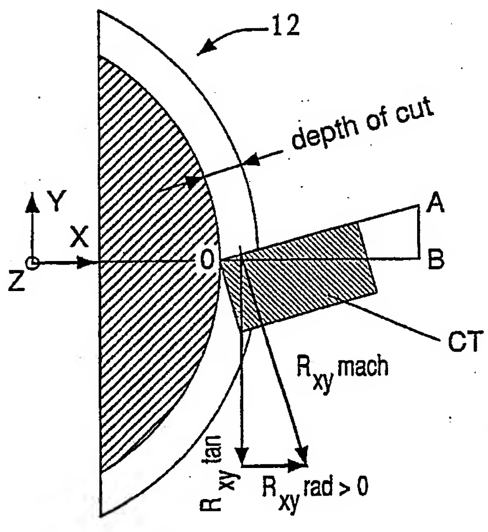

FIG. 4A
PRIOR ART

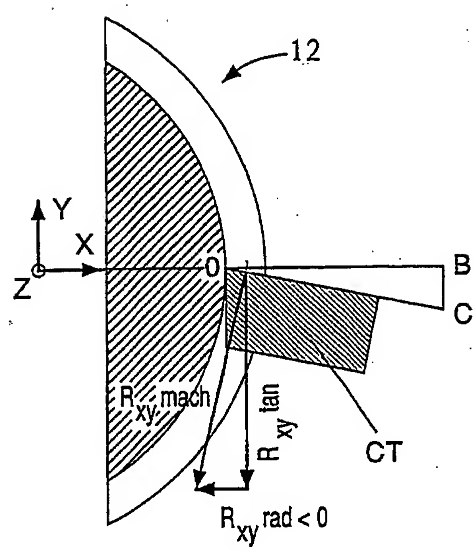

FIG. 4B

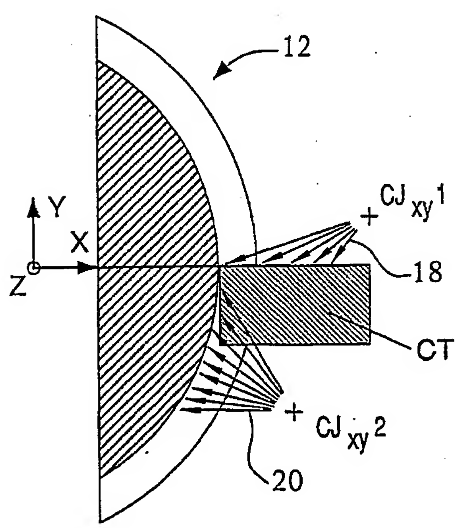

FIG. 4C

X-Y Plane Views